Renewable and Sustainable Energy Reviews 20 (2013) 364–377

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Progresses in inclined type solar stills

K. Kalidasa Murugavel [a,*], P. Anburaj [a], R. Samuel Hanson [b], T. Elango [c]

[a] Centre for Energy Studies, National Engineering College, K. R. Nagar-628503, Tamil Nadu, India
[b] Department of Mechanical Engineering, Infant Jesus College of Engineering, Kela Vallanadu-628851, Tamil Nadu, India
[c] Department of Mechanical Engineering, Udaya School of Engineering, Vellamodi-629204, K.K. District, Tamil Nadu, India

A R T I C L E I N F O

Article history:
Received 31 December 2011
Received in revised form
4 October 2012
Accepted 8 October 2012
Available online 9 January 2013

Keywords:
Desalination
Solar still
Inclined still
Productivity enhancement

A B S T R A C T

Basin type solar still is a simple device which can be used for fresh water production. The main drawback of a conventional basin solar still is the low amount of distilled water production per unit area which makes the single-basin solar still uneconomical. In inclined still, higher surface area and thin water surface are its advantages and maintaining continuous wetness along the inclined surface and loss of heat through raw water drain are the problems. This work reviews different methods used to improve the effectiveness on the inclined solar still so far by different researchers and compare their performances.

Contents

1. Introduction

More than two-thirds of the earth's surface is covered with water. Most of the available water is either present as seawater or icebergs in the Polar Regions. More than 97% of the earth's water is salty; rest around 2.6% is fresh water. Less than 1% fresh water is within human reach. As the available fresh water is fixed on earth and its demand is increasing day by day due to increasing population and rapid advancement of industry, there is an essential and earnest need to get fresh water from the saline/brackish water present on or inside the earth. Fresh water from saline/ brackish water can be obtained using different water treatment processes.

In the remote areas, people struggle to get pure water at a low cost. Solar desalination using still is the sustainable solution for this problem. Basin type still is simple and easy to fabricate but not economical due to its lower productivity. To increase the production, different designs were tried; inclined still is one such type. Comparatively, limited progresses were made in the improvements of inclined still. This paper consolidates and presents different efforts made to improve the productivity of the inclined solar still.

* Corresponding author. Tel.: +919677928940; fax: +914632232749.
E-mail addresses: kali_vel@rediffmail.com, hodces@nec.edu.in (K. Kalidasa Murugavel).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.10.047

2. Types of water treatment processes

Different water treatment processes were evolved to treat water using mechanical, electrical and thermal techniques such as micro-filtration, dialysis, distillation and freezing during the last decades. Table 1 lists some of the water treatment processes.

3. The need for solar Desalination

All the water treatment processes listed in Table 1 use a large amount of energy to remove a portion of pure water from a salt water source. Salt water (feed water) is fed into the process, and the result is one output stream of pure water and another of wastewater with a high salt concentration. It has been estimated by Kalogirou [1] that the production of 1000 m^3 per day of fresh water requires 10,000 t of oil per year. This is highly significant as it involves a recurrent energy expense which few of the water-short areas of the world can afford. Large commercial desalination plants using fossil fuel are in use in a number of oil-rich countries to supplement the traditional sources of water supply. Other countries in the world have neither the money nor oil resources to allow them to develop in a similar manner and because of this energy demand and high cost of plants, we prefer solar energy for the desalination process. Depending on the techniques adopted for evaporation and condensation, the solar desalination processes are classified as shown in Fig. 1.

4. Solar still

A solar still is a simple device which can be used to convert saline, brackish water into drinking water. Solar stills use exactly the same processes which in nature generate rainfall, namely

Table 1
Different water treatment processes.

Serial no.	Name of the type.	Description
1	**Reverse osmosis**	Here saline water is pushed at high pressure through special membranes allowing water molecules pass selectively and not the dissolved salts.
2	**Vapour compression**	Here water vapour from boiling water is compressed adiabatically and vapour gets superheated. The superheated vapor is first cooled to saturation temperature and then condensed at constant pressure. This process is derived by mechanical energy.
3	**Distillation**	Distillation is one of many processes that can be used for water purification. This requires an energy input, as heat, solar radiation can be the source of energy. In this process, water is evaporated, thus separating water vapour from dissolved matter, which is condensed as pure water.
4	**Multistage flash distillation**	The MSF process is combined of series of elements, called stages. In each stage condensing steam is used to pre-heat the seawater feed. By fractioning the overall temparature differential between the warm source and seawater into a large number of stages, the system approaches ideal total latent heat recovery. Operation of this system requires pressure gradients in the plant [2].
5	**Multiple-effect distillation**	Multiple-effect basin stills have two or more compartments. The condensing surface of the lower compartment is the floor of the upper compartment. The heat given off by the condensing vapor provides energy to vaporize the feed water above. Multiple-effect solar desalination systems are more productive than single effect systems due to the reuse of latent heat of condensation [3].
6	**Humidification and dehumidification**	In this system, air is used as a working fluid. This process is based on the principle of mass diffusion and utilizes dry air to evaporate saline water, thus humidifying the air. During dehumidication process, the vapor condenses and deliver pure water [3].
7	**Freezing**	The concept is appealing in theory because the lesser thermodynamic energy required for freezing than for evaporation since the latent heat of fusion of water is 6.01 kJ/mole while the latent heat of vaporization at 100 °C is 40.66 kJ/mole. In refrigeration freezing, a standard refrigeration cycle is used to cool the product water stream until ice forms. The ice is scraped off and melted [3].

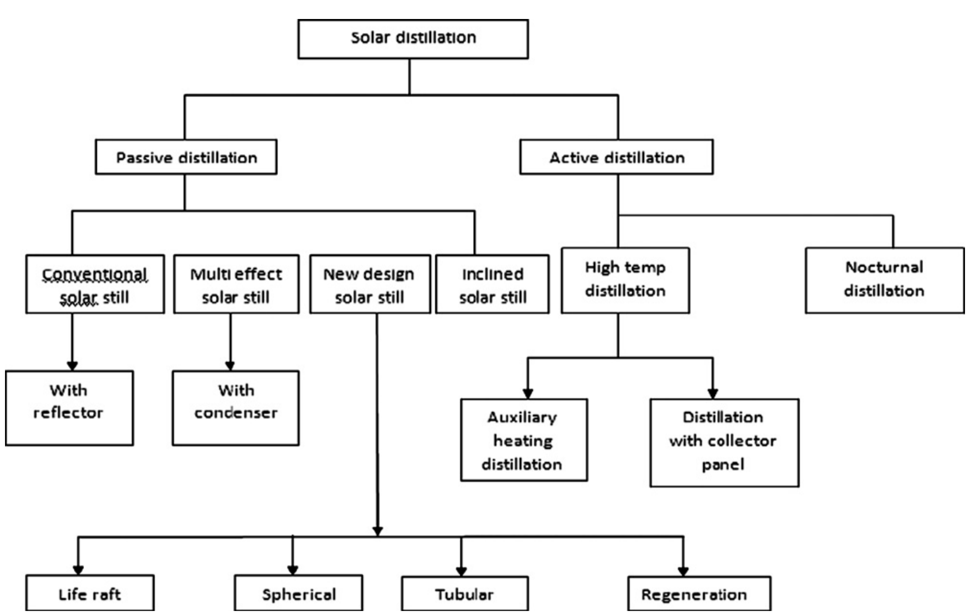

Fig. 1. Classification of solar distillation.

evaporation and condensation. Its function is very simple; a transparent cover encloses a pan of saline water and latter traps solar energy within the enclosure. This heats up the water causing evaporation and condensation on the inner face of the sloping transparent cover. This distilled water is generally potable; the quality of the distillate is very high because all the salts, inorganic and organic components and microbes are left behind in the bath. Based on the position of evaporation surface, the simple still can be classified as horizontal basin still, inclined still and vertical still. The following chapter discusses the developments and limitations of the basin still and other chapters discuss the developments in the inclined stills.

5. Basin stills

In this type of still, raw water is taken in a basin covered with inclined transparent cover. The water in the basin evaporates due to heating by sun's radiation and condenses at the lower surface of the transparent cover. Depending upon the altitude of the places and seasons, single and multi-slope stills are having different performances [4]. Different techniques were tried to improve the performance of these stills. Basin and cover temperatures are the main parameters. The production increases with the difference in temperature between basin and water [5]. Depending on the efforts taken to improve the performance, this still is further classified as passive and active stills.

5.1. Passive type stills

In passive type basin stills, glass cover plate with 3 mm thickness gives 16.5% more production than the cover with 6 mm glass thickness [6]. Tiwari et al. [7] conducted indoor simulation experiment and found that the production rate was higher for 30° cover inclination. Glass temperature affected the condensation rate at its lower surface. Lower glass surface temperature increases the circulation of air inside the still which enhances convective and evaporative heat transfer between basin water and glass. Also cooler glass lower surface increased condensation. The glass cover temperature was reduced by continuous flow [8] or intermittent flow [9] of raw cooling water on the cover. Tiwari et al.'s [10] results show that the daily yield was decreased about 44% when changing the water depth from 0.01 to 0.20 m with the initial water temperature as 35 °C. Contrarily, the yield was increased to about 25% when changing the water depth from 0.01 to 0.20 m with the initial water temperature as 50 °C. Addition of absorbing material in the basin increases the radiation absorption and productivity of the still. The maximum yield is obtained when the black materials (black dye, black cotton cloth and black rock) are used in the basin. Also the use of coal, charcoal, metallic sponge, fin plate and corrugated plate increases the productivity of the still significantly. The use of black rubber, black gravel and quartzite rocks also increases the productivity significantly. The use of asphalt with sprinkler in the basin increased the productivity at night also. The use of sponge cubes and jute cloths increased the evaporation area and the productivity. Internal and external mirrors in solar still increased the yield. An inclined external mirror increased the radiation available in the basin than the vertical mirror. The inclination of the mirror depends upon the latitude of the place.

5.2. Active type solar stills

In active type basin stills, some external sources are used to increase the temperature of water in the basin. The external sources connected with the simple basin still are flat plate collector, concentratic collector, hybrid PV/T system, heat exchanger, solar pond, multiple basins and additional condenser. Voropoulos et al. [11] experimentally investigated the conventional solar still coupled with a solar collector field and hot water storage tank. The results show significantly higher distilled water output compared with that of an uncoupled still. The productivity of the still reduced when hot water was drawn-off from the hot water storage tank. Dwivedi and Tiwari [12] studied a double slope active solar still under natural circulation mode. The results show that the active solar still gave 51% higher yield in comparison to the double slope passive solar still. Boubekri and Chaker [13] analyzed to improve the productivity of single slope solar still using flat plate collector, storage tank, internal and external mirrors. The results show that the increase in the production is due to the reflectors which is much more significant in winter 72.8%, in spring 40.33% and in summer 7.54%. The effect of the storage tank was also very significant in winter and summer. The daily productivity of the still coupled with the tank was about 27.54%, 21% and 23.28% respectively for winter, spring and summer. Shiv Kumar and Arvind Tiwari's [14] experimental result shows that 23% of the power generated by the PV module was used for running the DC pump motor and remaining 77% was used for other applications. The yield of this still was about 5.5 times higher than that of the passive still during winter months. The electrical efficiency of the PV module was in the range of 9.3–12.4%. Al Mahdi [15] conducted a transient analysis for the prediction of the performance of a multi-basin solar still. The analysis was applied to investigate the effect of the number of basins on the daily productivity of the still. The results show that the double-basin still gives the highest productivity peak. However, the triple- and quadruple-basin stills continue to produce appreciable amounts of distillate during the night, thereby leading to higher daily productivities. Result shows, increasing the number of basins beyond three does not yield significant improvements in the still productivity. The condensation rate can be increased by providing additional area for condensation. When a double slope still is used for higher latitude places, its one side cover receives the sun rays close to normal and the other side cover is in the shadow region for sun rays. Hence the other side can be used as an inbuilt condenser. Glass side cover is inclined with an angle equal to the latitude of the place to receive the sun rays close to normal and the distance between the cover and basin water is kept minimum, so that maximum volume of air with vapor purges into the condenser area [16].

5.3. Special designs

Velmurugan et al. [17] studied the effect of integrating the solar still with mini solar pond (Fig. 2). The average daily

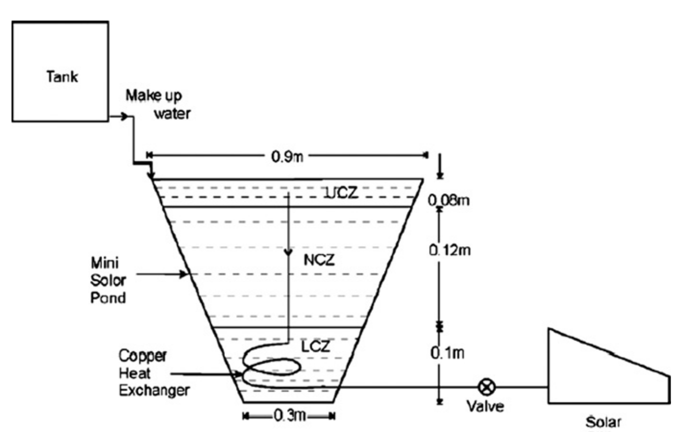

Fig. 2. Solar still with mini solar pond [17].

production of solar still was found to be increased considerably, when it was integrated with a mini solar pond. It was found that the optimum value of salinity in the mini solar pond is 80 g/kg of water. The average increase in productivity, when a pond was integrated with the still, was about 27.6%. The maximum deviation of the performance was 9% in comparison with that of the theoretical analysis. Thus, it augments the productivity of the solar still as shown in Fig. 3.

Kabeel [18] studied the performance of solar still with a concave wick evaporation surface (Fig. 4). A concave wick surface was used for evaporation, whereas four sides of a pyramid shaped still was used for condensation. Use of jute wick increased the amount of absorbed solar radiation and enhanced the evaporation surface area. A concave shaped wick surface increased the evaporation area due to the capillary effect. The results show that the average distillate productivity of the proposed still during the 24 h time was about 4.0 l/m^2 (Fig. 5). The proposed concave solar still efficiency reached about 45%.

Kalidasa Murugavel et al. [19] studied the effect of using spreader materials in the basin. In this work, a single basin double slope passive type solar still was fabricated and tested with a layer of water (approximately 2 mm depth) under controlled input conditions. This work compared the performance of a solar still with a layer of water in the basin with different basin spreader materials like cotton cloth, jute cloth and sponge sheet, and porous materials like washed natural rock and quartzite rock as spread materials (Fig. 6). From the different basin wick materials, light black cotton cloth was the most effective which yielded higher production per

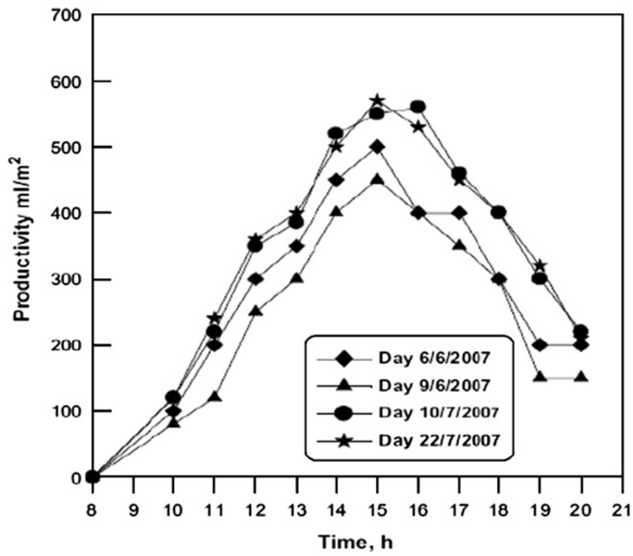

Fig. 5. Hourly variation of distillate output during different days [18].

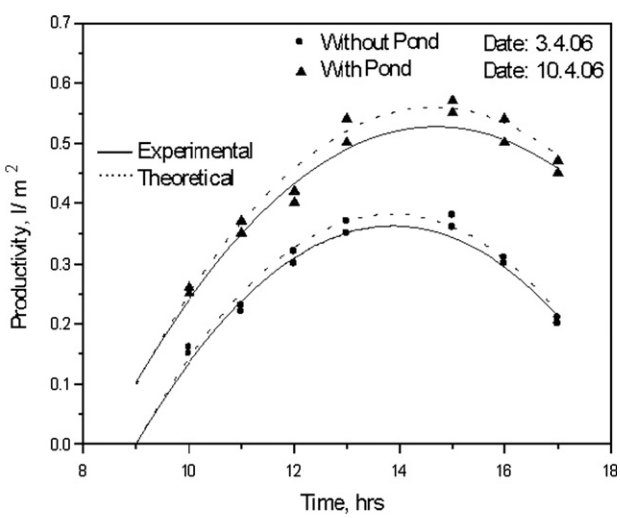

Fig. 3. Effect of integrating a solar pond with still on productivity [17].

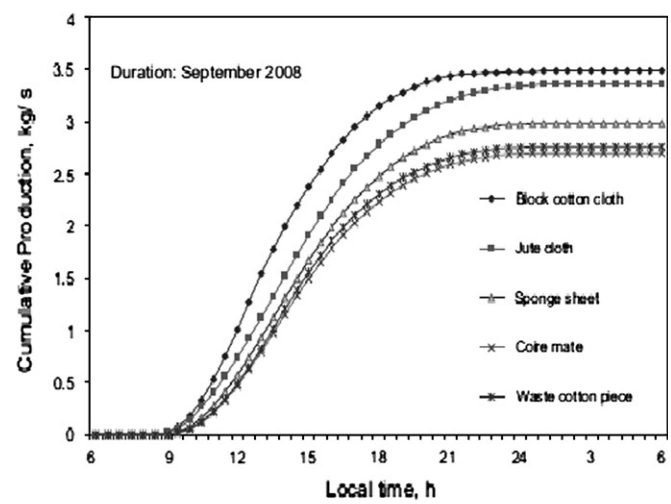

Fig. 6. Variations of cumulative production for different wick materials [19].

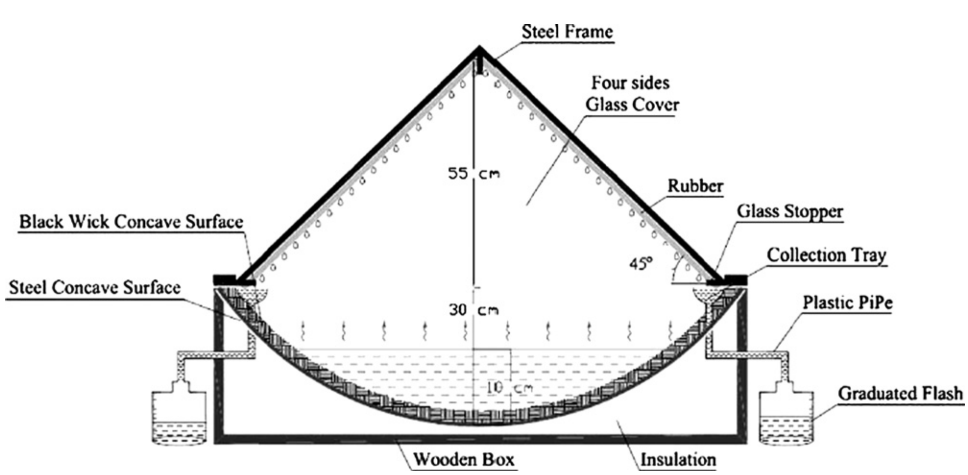

Fig. 4. Schematic diagram of concave wick solar still (drawn not to scale) [18].

day. With the different fin configurations in the basin, the aluminium rectangular fin covered with cotton cloth and arranged in length wise direction was more effective and gave slightly higher production than the light black cotton cloth. Rajaseenivasan et al. [20] reviewed the different methods to enhance the productivity of the multi-effect solar still and concluded that the double basin double slope solar still is efficient. The productivity was increased further when on each side of the upper basin was divided into three compartments to spread the water uniformly and it was maximum when iron pieces were used as energy storing material in the lower basin along with water [21].

The above discussion shows that the efficiency of basin stills varies with different modifications. But the maximum productivity achieved is low.

6. Inclined type stills

Depends on the techniques adopted to improve the evaporation rate, the inclined still are classified as show in Fig. 7. In the inclined type solar still, it is observed that, the longer flow of feed water increases the rate of evaporation. So it automatically increase the amount of distilled water. Further, with wick on the absorber plate, the productivity is increased by enhancing the evaporation area. In a wick still, the feed water flows slowly through a porous, radiation-absorbing pad (the wick). Two advantages are claimed over basin stills. First, the wick can be tilted so that the feed water presents a better angle to the sun (reducing reflection and presenting a large effective area).Second, less feed water is in the still at any time and so the water is heated more quickly to a higher temperature. Tanaka et al. [22] have proved the superiority of the tilted wick type solar still and confirmed an increase in productivity by 20–50%. Simple wick stills are more efficient than basin stills and some designs are claimed to cost less than a basin still of the same output. A simple multiple wick solar still made of frame of aluminum, a glass cover and a water reservoir made of galvanized iron was designed by Sodha et al. [23]. Foam insulation

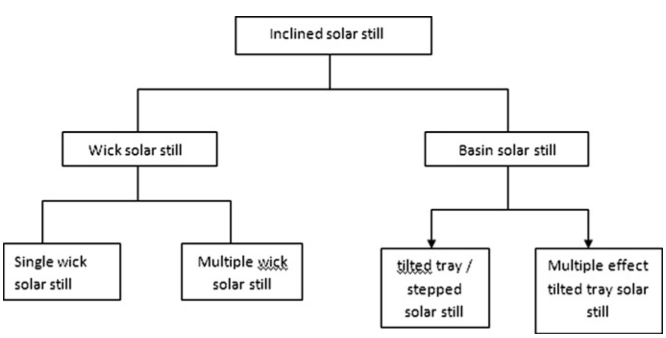

Fig. 7. Classification of inclined solar still.

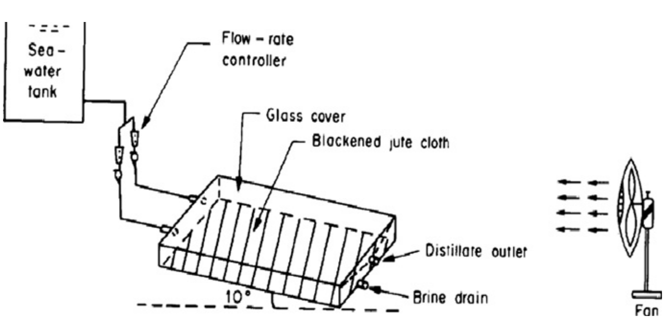

Fig. 8. Schematic diagram of an inclined wick-type solar distiller with artificial simulation [24].

was supported beneath the aluminum bottom by a net of nylon ribbon. The authors claimed the present design to offer several advantages including lightweight and low cost of the still and a significant output.

7. Developments in inclined solar still

Ho-Ming Yeh et al. [24] studied the effects of climatic, design and operational parameters on the performance of wick-type solar distillers (Fig. 8). In wick-type solar still, analysis was done on productivity with different insulation thickness. Experimental results show that distillers without insulation produce lower yields, especially for high values of insulation (Fig. 9).

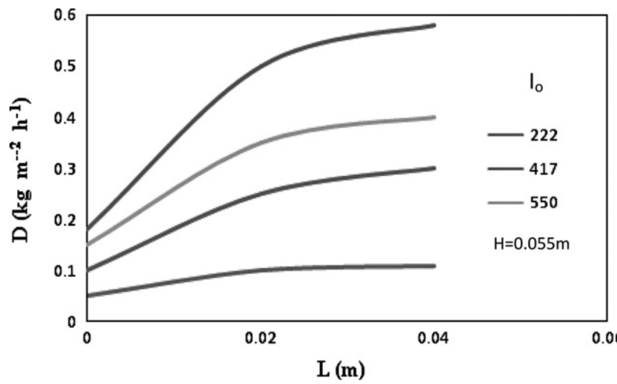

Fig. 9. The effect of insulation thickness on productivity [9].

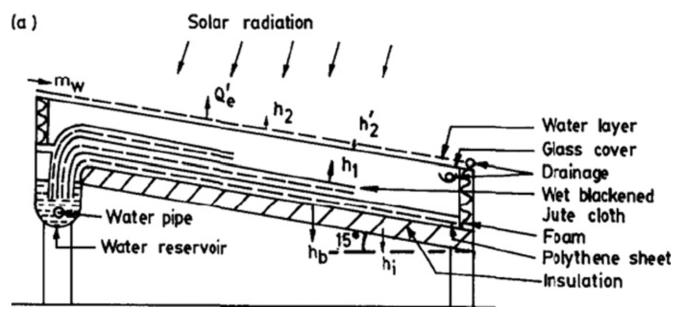

Fig. 10. multi-wick still [25].

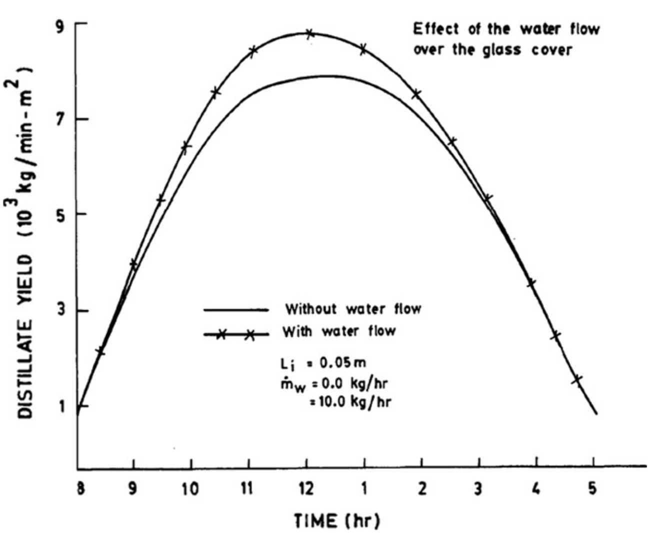

Fig. 11. Variation of the distillate with and without water flow over the glass covers [25].

Dhiman and Tiwari [25] studied the effect of water flowing over the glass cover of a multi-wick solar still (Fig. 10). In this paper, an analytical model of a multi-wick solar still with flowing water over the glass cover had been presented. Fig. 11 presents the effect on the distillate output of water flowing on the glass cover. It shows that the distillate is more in the case when water is flowing over the glass cover in a very thin layer. The reason for this is the increased difference between the temperatures of the water in the still and the glass cover. The output was increased by 10% approximately.

Minasian et al. [26] studied the performance of improved wick-basin type (Fig. 12). In this paper, a new type of still was formed by connecting a small conventional basin-type (installed in shadow and having an opaque cover) with a wick-type solar still so that the hot waste brine water leaving the wick-type will feed directly the basin-type. The wick-basin type solar still was economically the best when compared with each of the wick-type and the basin-type solar still (Fig. 13). It was shown that the overall efficiency of this new still was higher than the other two investigated stills. Moreover, the total yearly amounts of distilled water indicate that the wick-basin type could produce 85% more than the basin-type and 43% more than the wick-type solar still.

Sodha et al. [27] studied the performance of a multiple wick solar still (Fig. 14) and compared the theoretical and experimental performance (Fig. 15). In this, blackened wet jute cloth formed the liquid surface which was oriented to intercept maximum solar radiation and to attain high temperatures on account of low thermal capacity. The wet surface consisted of a series of jute cloth pieces of increasing length separated by thin black polythene sheets, resting on foam insulation supported by a net of nylon ribbon; these pieces were arranged along an incline and their upper edges are dipped in a saline water tank. Suction by the capillary action of the cloth fiber provides a thin sheet of liquid on the cloth; the arrangement ensures that all the surface, irradiated by the sun was wet at all times. The results show that on a typical cold sunny day in Delhi (viz. 6 February 1980) the distillate output was 2.5 l/m^{2}day, corresponding to an overall efficiency of 34 per cent (as compared to a maximum of 30 per cent for basin type still). The still costs less than half of the cost of a basin type still of same area and provides a higher yield of distillate.

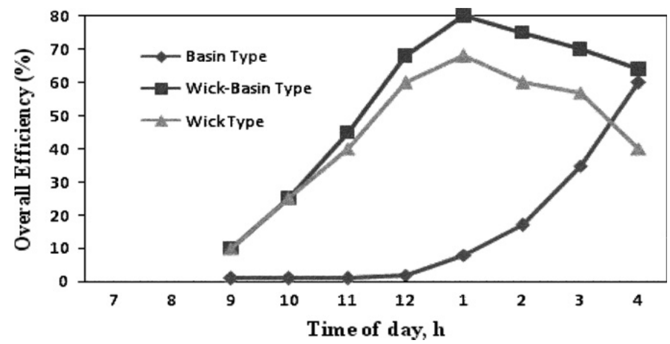

Fig. 13. Efficiency of stills [24].

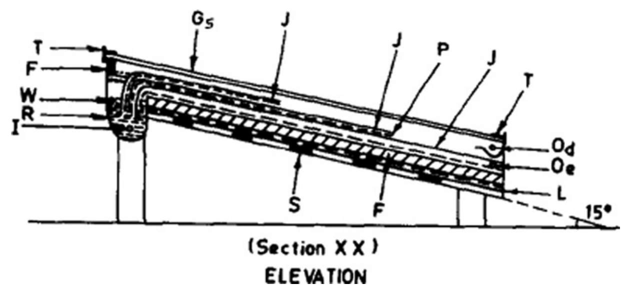

Fig. 14. Multi-wick solar still [27].

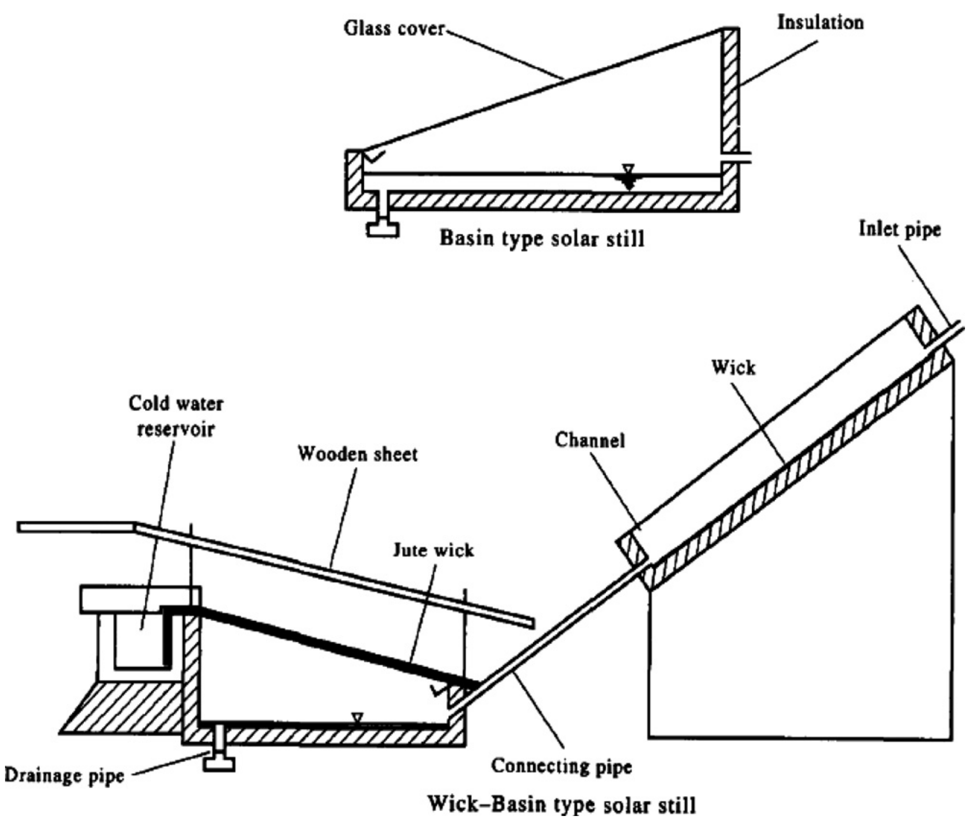

Fig. 12. Experimental stills [26].

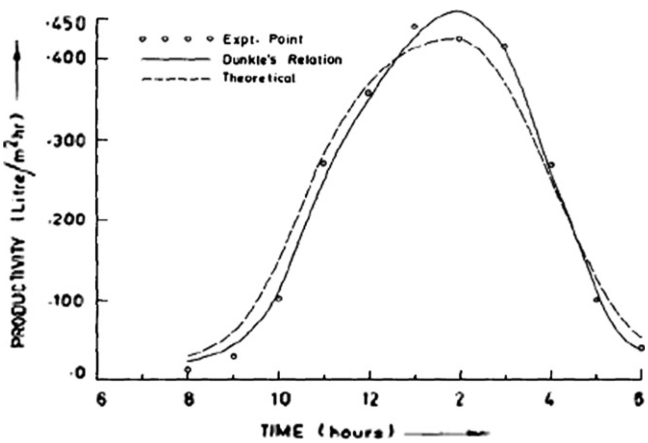

Fig. 15. Hourly variation of distillate yield [27].

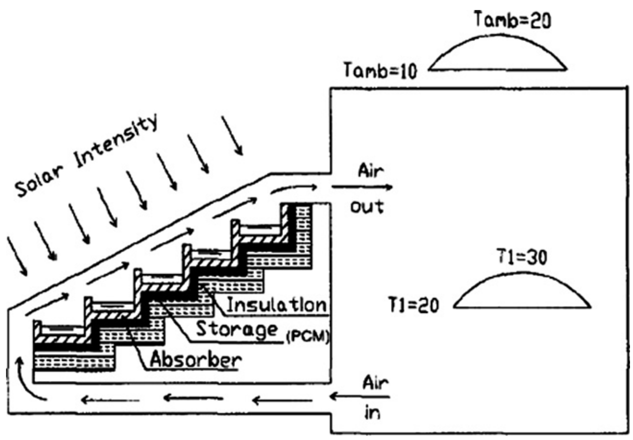

Fig. 16. Solar still with built-in LHTESS [28].

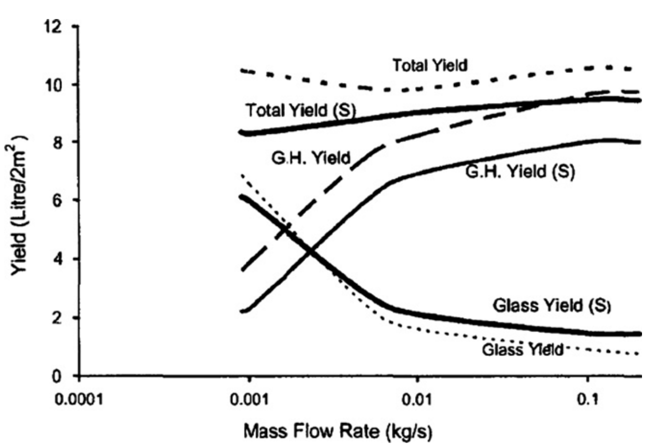

Fig. 17. Effect of mass flow rate on water yield [28].

Radhwan [28] studied the transient performance of a stepped solar still with built-in latent heat thermal energy storage (Fig. 16). The still was designed for heating and humidification of agriculture greenhouses (GH) in remote areas. The solar still consisted of five stepped basins with an inclined glass cover and is insulated on the bottom. The basin was placed on a slab filled with a layer of paraffin wax (phase change material, PCM) that acts as a latent heat thermal energy storage system (LHTESS). Air from GH entered the still from the bottom, flows between the basins and glass cover where it was heated and humidified, and then flows back into the GH. The still performance parameters investigated were analyzed, and the results were compared with the case of a still without the LHTESS (Fig. 17). The still temperature as well as outlet air temperature and GH heat load were more uniform compared to the sinusoidal trends for the still without LHTESS. It was found that the relative humidity of circulating air increased along the still and always leaves at saturation conditions. The results indicated that decreasing the air flow rate has an insignificant influence on the still yield, while the GH heat load experienced a decrease.

Badran et al. [29] studied on simulation and experimentation for an inverted tickle solar still (Fig. 18). The still was basically composed of an inclined absorber plate painted black on the top. Saline water flowed at the backside of the plate and was kept attached to the plate. The water flow rate was kept low so that its temperature was raised to produce vapor. Condensation took place in another compartment where a heat exchanger was placed to provide heat recovery. This represented an 18% increase in this kind of output over previous work, which was due to reduction in the salinity of feed water. However, the intermediate header production, which was saline water of reduced salinity (3600 ppm), was also reduced by 13%. A computer simulation program was developed to predict the performance of the still (Fig. 19).

Aybar et al. [30] studied on an experimentation of inclined solar water distillation system (Fig. 20). Unlike solar stills, the feed water fell down on the absorber plate, and the system produced fresh water and hot water simultaneously. It was suspected that the longer the flowing water was held on the absorber plate, the greater the evaporation, leading to an increase in the amount of distilled water. The system can generate 3.5–5.4 kg/d distilled water (for a 1 m^2 absorber plate area). The temperature of the generated hot water was about 40 °C, which is good enough for domestic usage. The simulation results were in good agreement with the experimental results.

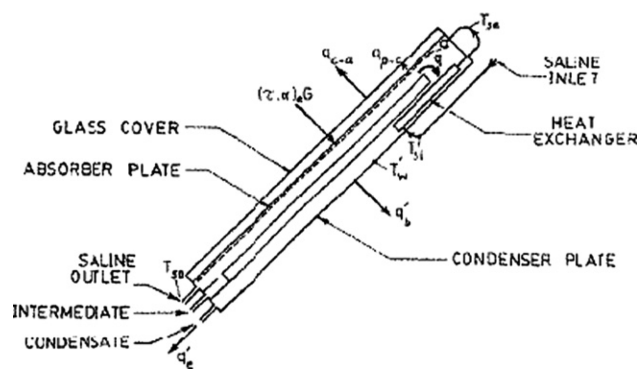

Fig. 18. Schematic diagram of the still [29].

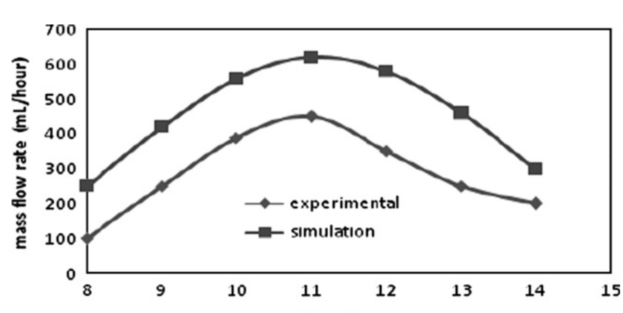

Fig. 19. Productivity vs. time [27].

Janarthanan et al. [31] studied the performance of floating cum tilted-wick type solar still with the effect of water flowing over the glass cover (Fig. 21). A simple transient performance of floating cum tilted-wick type solar still had been presented by incorporating the effects of water flowing over a glass cover, heat capacity of tilted-wick water surface and floating-wick water surface. Explicit expressions for flowing water, glass, tilted-wick water surface and floating-wick water surface temperature and efficiency of the system had been derived. The results indicated (Fig. 22) that the relative standard deviations between theoretical and experimental results were less than 8% (glass cover), 2% (tilted wick water surface), 1% (floating-wick water surface) and 2% (flowing water at the lower end of the glass cover) an average for the working hours of the day.

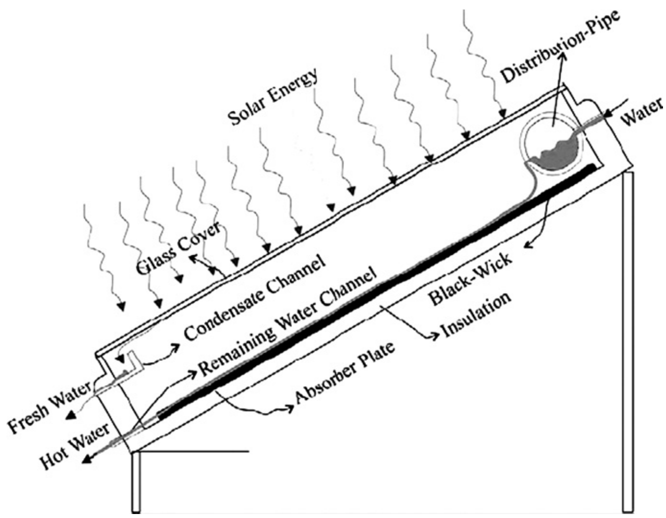

Fig. 20. Schematic diagram of inclined solar water distillation system [30].

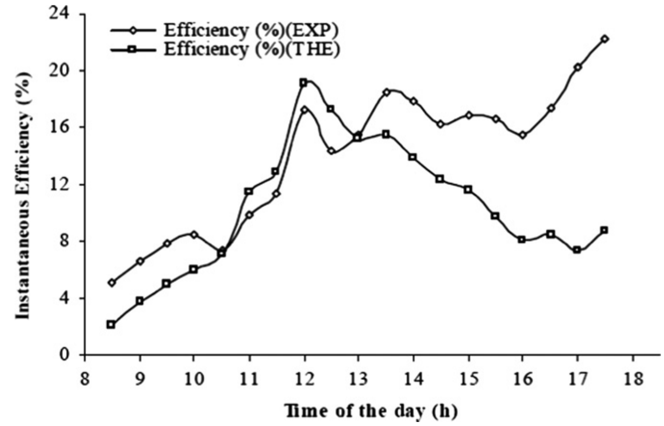

Fig. 22. Instantaneous variations of experimental and theoretical efficiency of the still [31].

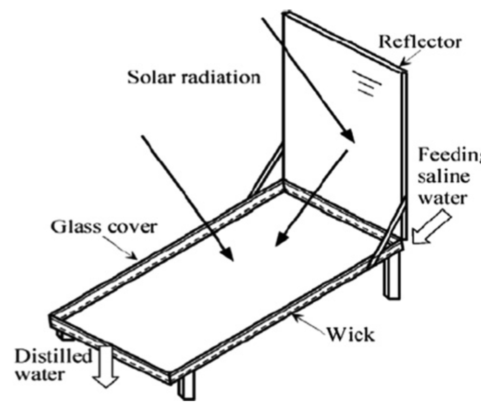

Fig. 23. Schematic diagram of tilted wick still with vertical flat plate external reflector [32].

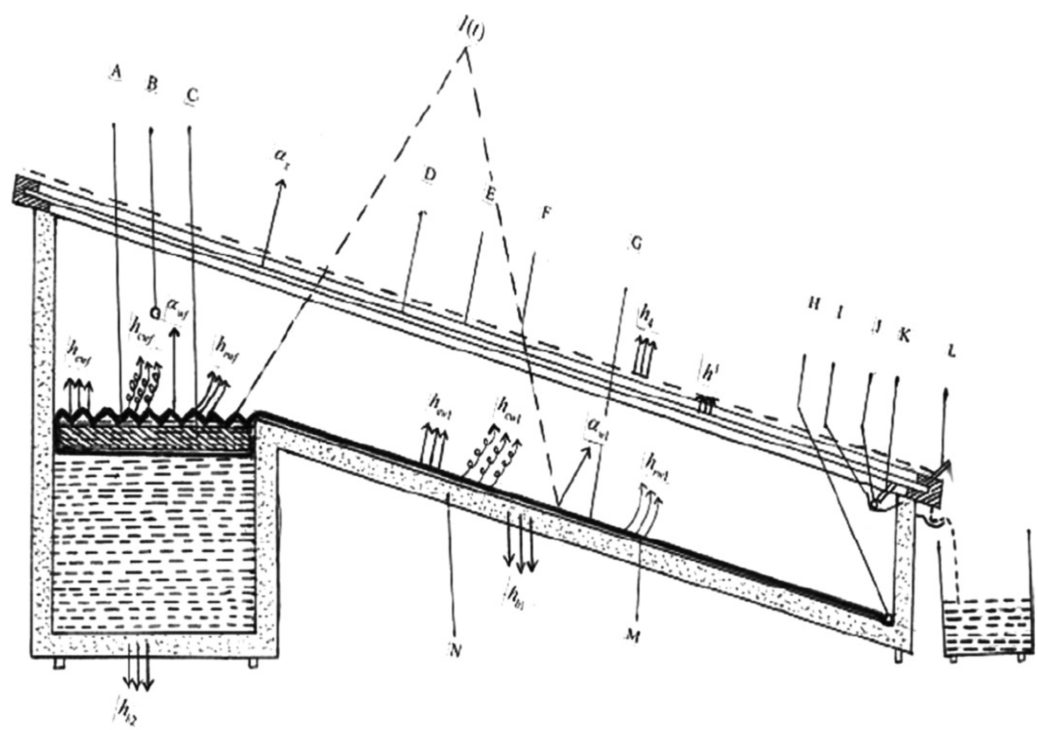

Fig. 21. Sectional view of the still with water flowing over the glass cover [31]. A-Floating-wick surface, B-Constant water level inlet, C-Thermocole, D-Glass cover of 4 mm thickness, E-Wooden frame to hole the glass cover, F-Water flowing over the glass cover, G-Tilted-wick surface, H-Excess hot saline water outlet, I-Distilled water collection channel, J-Distilled water outlet, K-Glass piece, L-Glass piece, M-Glass wool insulation and N-Inner GI cover.

Tanaka et al. [32] studied the improvement of the tilted wick solar still by using a flat plate reflector (Fig. 23). This paper presented a numerical analysis to investigate the effect of the vertical flat plate external reflector on the distillate productivity of the tilted wick solar still (Fig. 24). They proposed a geometrical method to calculate the solar radiation reflected by the external reflector and absorbed on the evaporating wick, and also performed numerical analysis of heat and mass transfer in the still to predict the distillate productivity for four days. They found that the external reflector can increase the distillate productivity in all but the summer seasons, and the increase in the daily amount of distillate averaged over the four days was predicted to be about 9%.

Sadineni et al. [33] studied the theoretical and experimental performance of a weir-type inclined solar still (Fig. 25). A weir-type solar still was proposed to recover rejected water from the water purifying systems for solar hydrogen production. This consisted of an inclined absorber plate formed to make weirs, as well as a top basin and a bottom basin. Water was flowed from the top basin over the weirs to the bottom collection basin. A small pump was used to return the unevaporated water to the top tank. Hourly distillate productivity of the still with double- and single-pane glass covers was measured and the latter showed higher production rates (Fig. 26). The average distillate productivities for double- and single-pane glass covers were approximately 2.2 and 5.5 l/m2/day in the months of August and September in Las Vegas, respectively.

Tanaka et al. [34] studied one step azimuth tracking tilted-wick solar still with a vertical flat plate reflector (Fig. 27). The still was assumed to be rotated manually just once a day at southing of the sun. They performed numerical analysis of heat and mass transfer in the still to determine the distillate productivity of the still on four typical days: the spring and autumn equinox and summer and winter solstice days at 30°N latitude. They found that the increase in the daily amount of distillate of a tilted-wick still would average about 41% for four days, and can be achieved by the simple modification of using a flat plate reflector, setting the still at proper tilt angle according to seasons and rotating the still just once a day. The daily amount of the proposed still was about 40%, 57%, 40% and 27% greater than that of the conventional tilted-wick still on the spring equinox, summer solstice, autumn equinox and winter solstice, respectively (Fig. 28).

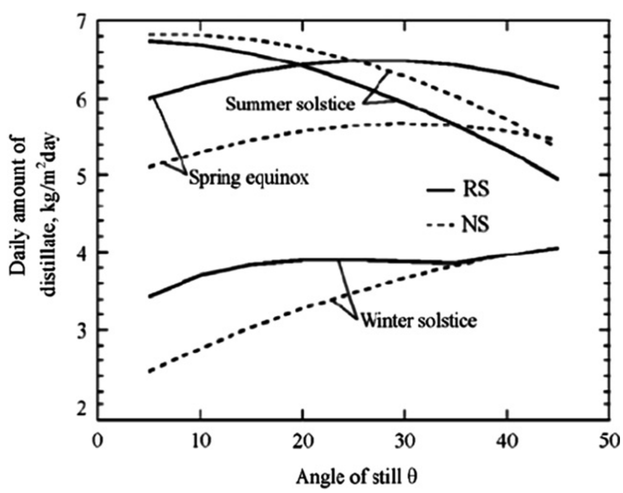

Fig. 24. Variation of daily amount of distillate with angle of still on the spring equinox and the summer and winter solstices [32].

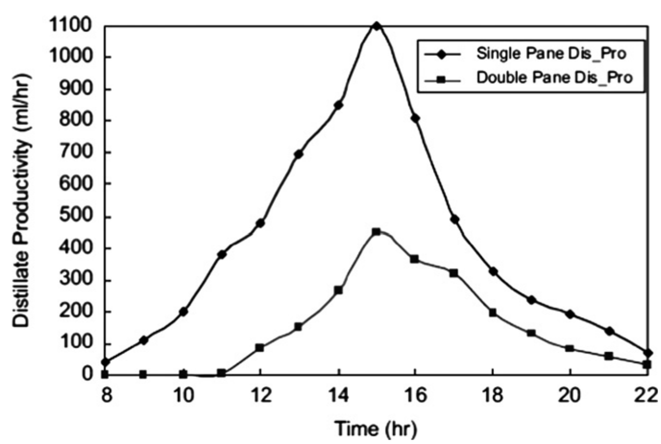

Fig. 26. Comparison of distillate productivity from the still with single- and double-pane glasses [33].

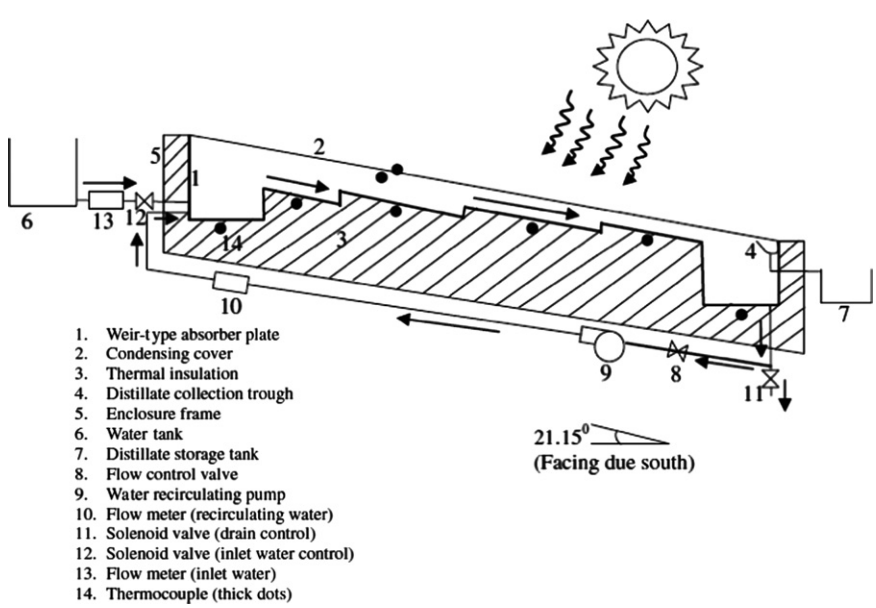

Fig. 25. Schematic of the weir-type solar still [33].

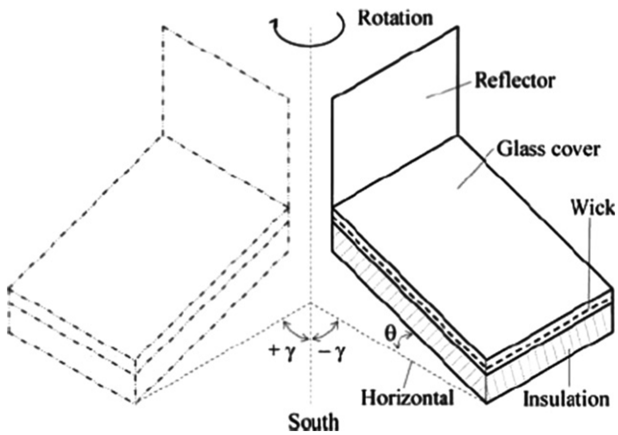

Fig. 27. Schematic diagram of one step azimuth tracking tilted-wick solar still with vertical flat plate reflector [34].

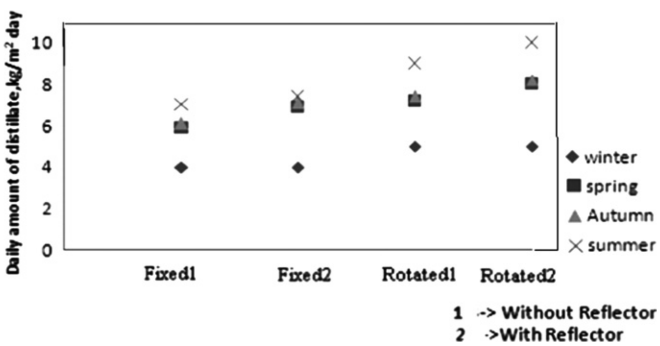

Fig. 28. Daily amount of distillate of the various types of stills on the spring and autumn equinox, and summer and winter solstice at 30°N [34].

Velmurugan et al. [35] studied the performance of stepped solar still for effluent desalination (Fig. 29). In this work, a stepped solar still and an effluent settling tank were fabricated and tested for desalinating the textile effluent. The effluent was purified in an effluent settling tank. In this tank, large and fine solid particles were settled and clarified. The settled effluents were used as raw water in the stepped solar still. For better performance, the stepped solar still consisted of 50 trays with two different depths. First 25 trays with 10 mm height and the next 25 trays with 5 mm height were used. Fin, sponge, pebble and combination of the above were used for enhancing the productivity of the stepped solar still. The production rate increased by 53.3% when fins were used in the stepped solar still. When sponge and pebble were used, the productivity increased by 68% and 65% respectively. An

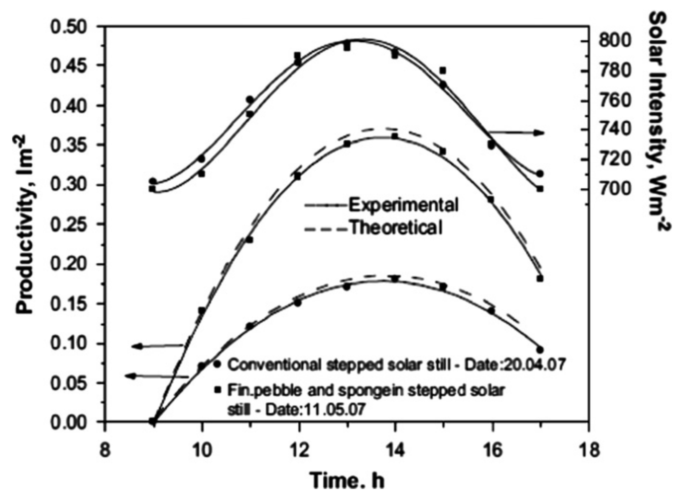

Fig. 30. Comparison of theoretical and experimental performance [35].

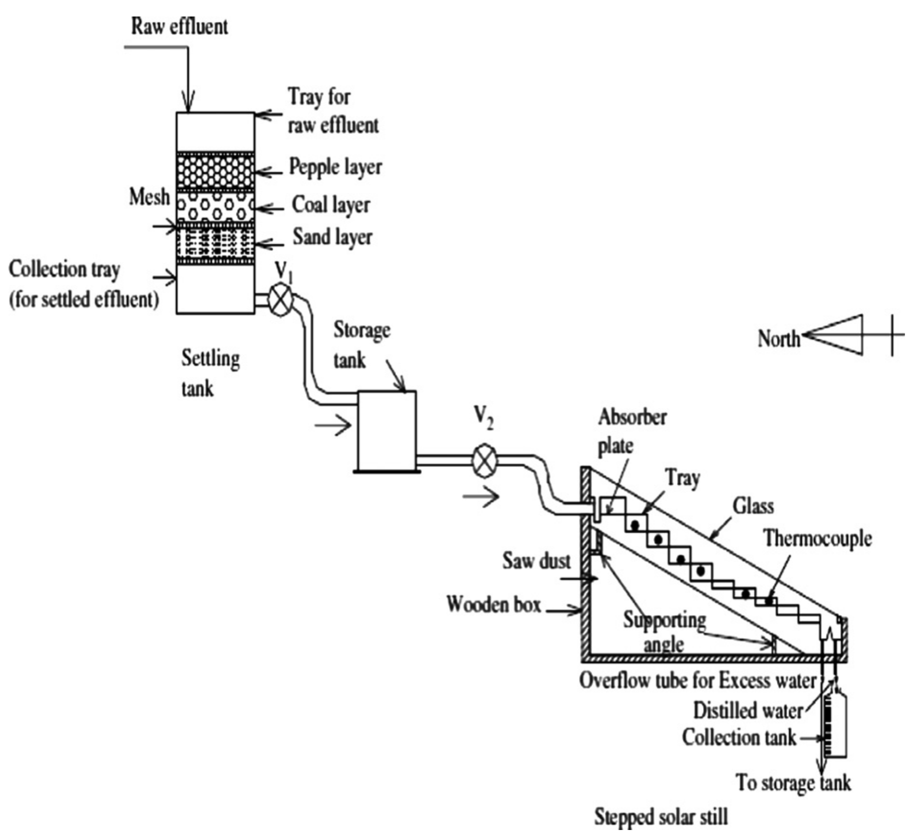

Fig. 29. Schematic diagram of the experimental setup [35].

attempt was made by using both sponge and pebble in fin type stepped solar still and productivity increased by 98% than the conventional stepped solar still. Effluent was used as feed. Theoretical predictions closely agreed with the experiment result (Fig. 30). The maximum deviation between theoretical and experimental analyses was less than 10%.

Velmurugan et al. [36] studied the integrated performance of stepped and single basin solar stills with mini solar pond (Fig. 31). An attempt was made to enhance the productivity of the solar stills by connecting a mini solar pond, stepped solar still and a single basin solar still in series. Experiment was also carried out by replacing the single basin solar still into a wick type solar still. For further augmentation of the yield, baffle plate, pebble, fins, wicks and sponges were added. The results showed that for the set of experiments, a mini solar pond, stepped solar still and wick type solar still were connected in series. Pebbles, baffle plates, fins and sponges were used in the stepped solar still for further productivity augmentation. The productivity during day and night

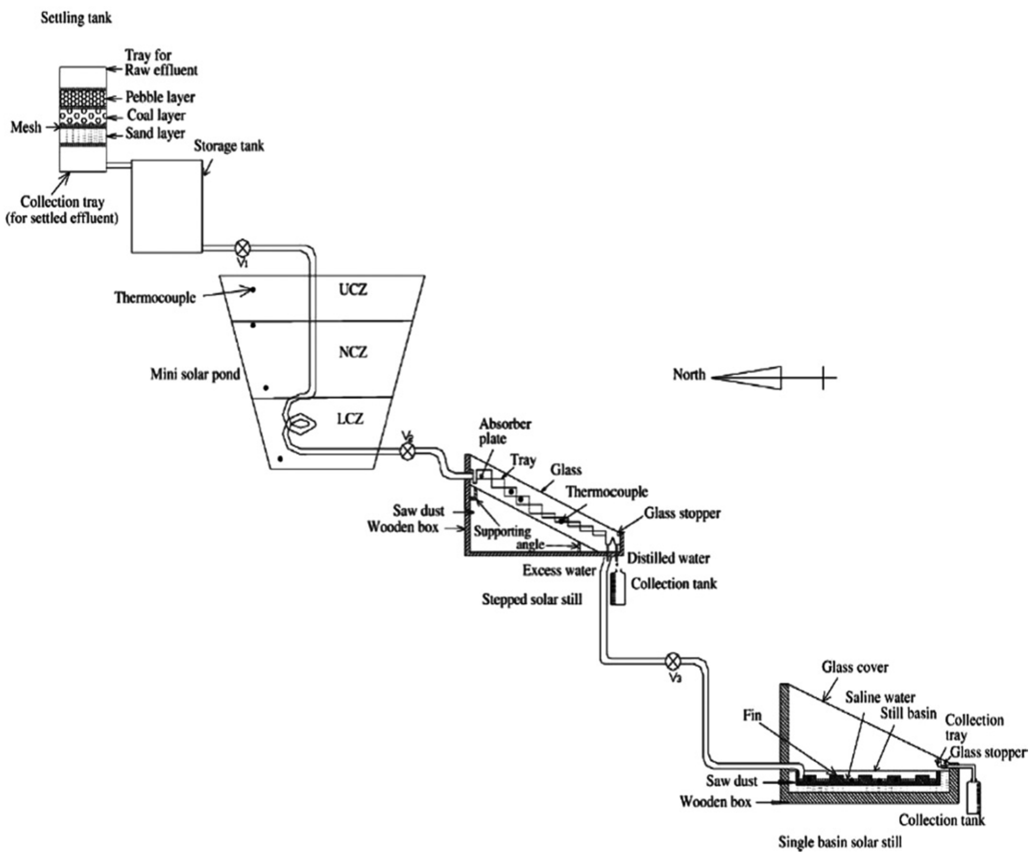

Fig. 31. Combination of stepped solar still and single basin solar still with solar pond [36].

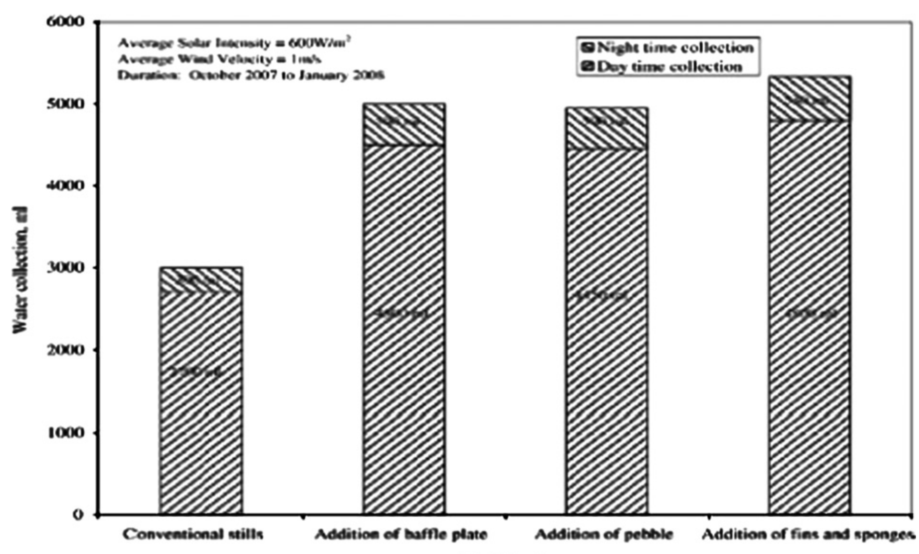

Fig. 32. Day and night water collection in stepped and wick type solar stills with solar pond [36].

were calculated. It was found that maximum productivity of 78% occurred, when fins and sponges were used in the stepped solar still (Fig. 32).

Tabrizi et al. [37] experimentally investigated a weir-type cascade solar still with built-in latent heat thermal energy storage system (Fig. 33). Here two cascade solar stills were constructed with and without latent heat thermal energy storage system (LHTESS). Paraffin wax was selected as the phase change material (PCM) which acted as a LHTESS. Using weir on each step caused an increase in residence time. Furthermore, a thin layer of water covered the evaporation surface and reduced channelization. The results showed that the total productivity of still without LHTESS was slightly higher than the still with LHTESS in sunny days. There was a significant difference in productivity of still: 3.4 kg/m2day for still with LHTESS and 2.1 kg/m2day for still without LHTESS in partially cloudy day. Thus, still without LHTESS was preferred for sunny areas because of its simplicity and low construction costs and still with LHTESS was proposed for partially cloudy areas due to the higher productivity and its stable condition regard to change in the weather conditions. Increase in flow rate resulted in decrease in the total productivity (Fig. 34). Highest total productivity achieved in the lowest possible flow rate (0.055 kg/min) were about 4.85 and 5.14 kg/m2day for still with and without LHTESS in the sunny day (23/05/2009), respectively.

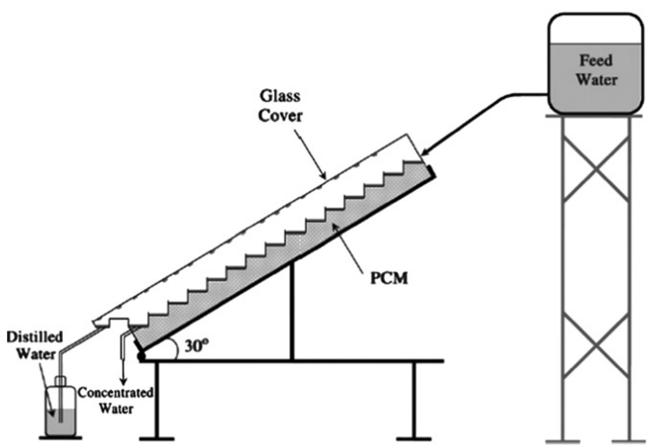

Fig. 33. Cross sectional view of a schematic diagram of cascade solar still [37].

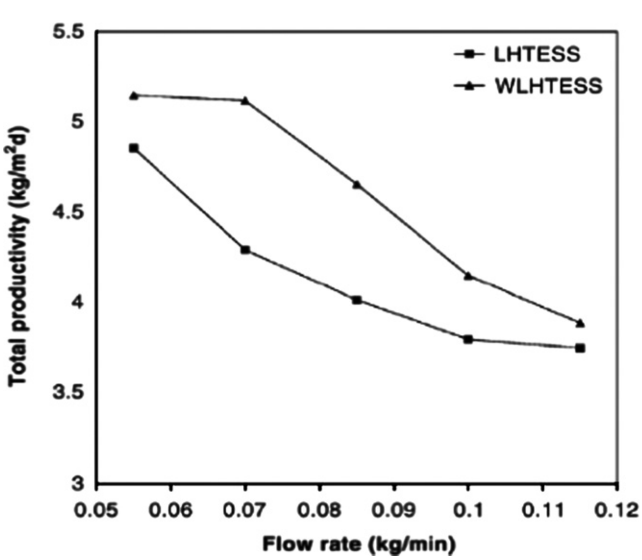

Fig. 34. Variations of total productivity with various flow rates [37].

Mahdi et al. [38] studied an experimental wick-type solar still system (Fig. 35). A tilted wick-type solar still was designed and constructed. Its practical aspects and performance were presented. Charcoal cloth was used as an absorber/evaporator material and for saline water transport. The results show that the daily efficiency of the still was about 53% on clear days in summer. It had been concluded that, the charcoal cloth was a good material for use as an absorber/evaporator and also as a water transport medium. Increase of the input water mass flow rate leads to a reduction in the efficiency of the wick-type solar still. The still efficiency decreased linearly with increase in salinity of the input saline water Fig. 36.

Abdul and Hussein [39] studied the effect of inclination of the external reflector on a simple inclined solar still in winter. Its practical aspects and performance are presented. The experimental investigation on the productivity with internal and external reflector tilted at angles of 0° (vertical), 10°, 20° and 30° and for still cover angles of 20°, 30° and 40° were carried out. For cover angle inclination of 20° and external reflector inclined of 20°, the productivity would be around 2.45 times that of simple still with no reflectors.

El-Zahaby et al. [40] studied the enhancement of corrugated steeped solar still performance using a reciprocating spray feeding

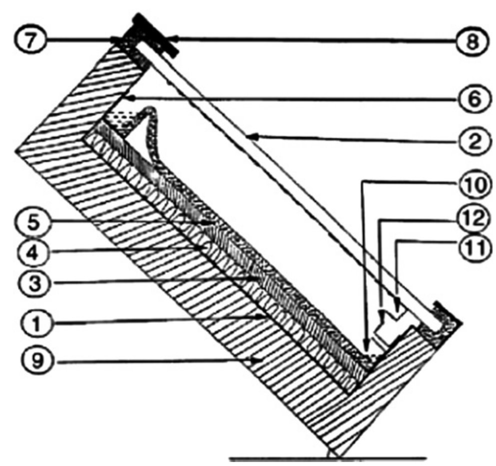

Fig. 35. Cross sectional view of the solar still [38]. In above Fig. (1) Galvanised steel tray, (2) glass cover, (3) support board, (4) polystyrene, (5) charcoal cloth, (6) aluminum channel, (7) rubber gasket, (8) steel strip, (9) styrofoam, (10) brine gutter, (11) distillate gutter, and (12) distillate outlet channel.

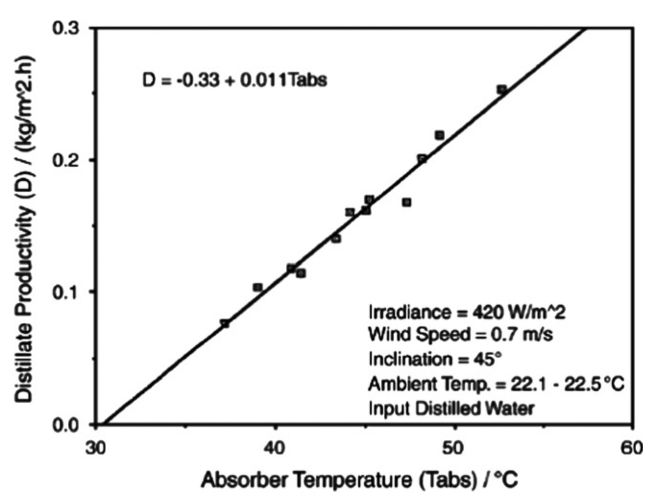

Fig. 36. Variation of distillate productivity with absorber temperature, (determined by indoor testing) by varying the flow rate [38].

Table 2
Comparative study on inclined type still.

Type of still	Author(s) and testing place	Specifications/ Materials	Results	Remarks
Wick type solar still.	Ho-ming yeh and Lie-chaing chen, Taiwan [24].	Inclination of the basin-10°	They conclude as distillers without insulation produce lower yields, especially for high values of insolation.	Insulation must need to improve the efficiency for all climatic zones.
Multi-wick solar still.	Dhiman and Tiwari,new delhi [25].	Inclination of the basin-15°	It shows that the distillate is more in the case when water is flowing over the glass cover in a very thin layer. The output is increased by approx. 10%.	There was no significant effect of changing the thickness of the insulation at the bottom on the distillate output, because of the low thermal capacity of water.
Wick-basin type solar still.	Minasian and Al-karaghouli, Baghdad, Iraq [26].	Area of basin still- 1.5×0.67 m. Area of wick still- 1.4×0.72 m. Inclination of the basin-15°.	The total yearly amounts of distilled water indicate that the wick-basin type could produce 85% more than the basin-type and 43% more than the wick-type solar still.	The results of the analysis showed that the wick-basin type solar Still was economically the best when compared with each of the wick-type and the basin-type solar still.
Stepped solar still with latent heat thermal energy storage system.	Radhwan, Jeddah Saudi Arabia [28].	Paraffin wax and Glauber's salt are typical phase change materials	The results showed that the still with latent heat thermal energy storage system has an efficiency of 57%, and the total daily yield is about 4.6 L/m 2.	Decreasing the air flow rate has an insignificant influence on the still yield, while the green house heat load experiences a decrease.
Inverted tickle type solar still.	Badran et al., amman, Jordan [29].	Tilt angles are 47 ° and 32°.	The productivity increased from 2.5 to 2.8 L/d when the salinity of the water was reduced from that of seawater (35,000 ppm) to brackish water (6000 ppm).	Decreasing the feed water flow rate down to 0.7 g/s substantially increases the productivity.
Floating cum tilted-wick type solar still	Janarthanan et al., Coimbatore, India [31].	Inclination of the basin-15°	The results indicate that the relative standard deviations between theoretical and experimental results are less than 8% (glass cover), 2% (tilted wick water surface), 1% (floating-wick water surface) and 2% (flowing water at the lower end of the glass cover) an average for the working hours of the day.	Glass cover temperature decreases significantly due to the water flowing over the glass cover which causes fast evaporation during peak sunny hours.
Tilted wick solar still	Hiroshi Tanaka, Yasuhito Nakatake, Fukuoka, japan [32].	Height-10 mm. Area of the basin-1×1 m.	The average daily amount of distillate of the still with the reflector is predicted to be about 9% larger than that of the still without the reflector.	The vertical flat plate external reflector would be less effective for the tilted wick still than for the basin still
Weir-type inclined solar still	Sadineni et al., Las Vegas, USA [31].	Inclination of the basin-21.15°	The productivity of the weir-type still is approximately 20% higher than the conventional solar still.	There is a significant reduction in the performance with double-pane glass compared with a single-pane glass.
Inclined type solar still	Aybar et al., north Cyprus, turkey [30].	Height-0.2 m. Area of the cavity-1×1 m.	The system can generate 3.5–5.4 kg (per m^2 absorber plate area) distilled water during a day (i.e., 7 am till 7 pm).	The fresh water generation rate increased two to three times when wicks were used instead of a bare plate.
Weir-type cascade solar still with built-in latent heat thermal energy storage system	Tabrizi et al., Zahedan, Iran [37].	Evaporation surface area- 0.45 m^2.Tilt angle-30°.	The maximum of total productivity for stills with and without LHTESS are 4.85 and 5.14 kg/m^2day respectively which achieved in lowest possible flow rate (0.055 kg/min).	The still with LHTESS produces the distillated water during the lack of sunshine, but its total productivity is slightly lesser than still without LHTESS because of more production during the sunshine by still without LHTESS.
wick-type solar still	Mahdi et al., Iraq [38].	Rectangular cross section of the channel- 15 mm $\times$ 20 mm	The representative daily efficiency of the still was about 53% on clear days in summer.	The still efficiency decreased linearly with increase of salinity of the input saline water e.g. it decreased, by indoor testing, from 37.7% to 20% as the NaCl salt concentration increased from 0% to 10% by weight.

system. Feeding of the saline water in the form of fine droplets into the still was controlled by a transverse reciprocating spraying system. An accumulated productivity of 6.355 l/m^2 in 10 hours with an efficiency of 77.35% was achieved.

Helmy et al. [41] studied the experimental performance of an inclined solar still with moving cloth wick. The cloth wick was driven by a DC motor. The cloth wick was subjected to solar radiation when the motor is in OFF and immersed in water when the motor is ON. Results showed that, with an ON period 30 seconds and OFF period 25 minutes, yield and thermal efficiency were maximum.

Kabeel et al. [42] conducted experiments on two solar stills simultaneously; a conventional single sloped solar still and a modified stepped solar still. The influence of depth and width of trays on the performance of the stepped solar still were investigated. Feed water temperature to the stepped still was varied using a vacuum tube solar collector. For further augmentation of the yield, a wick on the vertical sides was added to the stepped still. It is found that maximum productivity of stepped still was achieved at a tray depth of 5 mm and tray width of 120 mm, which is about 57.3% higher than that of the conventional still (Table 2).

8. Conclusion

The above investigation presents a clear view progresses made to improve the productivity of the different types of inclined solar still using different techniques. This section summarizes and presents the investigations carried out:

- The inclination of basin referred with the sun angle could bring good efficiency.
- The distillate is more in the case when water is flowing over the glass cover in a very thin layer.
- The combined wick and basin could produce high efficiency compared to the normal basin type stills.

- The provision of latent heat thermal energy storage could enhance the overall efficiency of the still.
- Decreasing the feed water flow rate down to 0.7 g/s substantially increases the productivity.
- The reduction in salinity of the feed water could improve the productivity.
- The average daily amount of distillate of the still with the external reflector is larger than that of the still without the reflector.
- The fresh water generation rate increased two to three times when wicks were used instead of a bare plate.
- The various wick materials like jute cloth, sponge sheets, black cotton cloth and coir mate were used to improve the distillate output. Among these black cotton cloth produced good efficiency.

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